Developing action thresholds for codling moth (Lepidoptera: Tortricidae) with pear ester- and codlemone-baited traps in apple orchards treated with sex pheromone mating disruption

A.L. Knight[1]

Yakima Agricultural Research Laboratory, USDA–ARS, 5230 Konnowac Pass Road, Wapato, Washington 98951, United States of America

D.M. Light

Western Regional Research Center, USDA–ARS, 800 Buchanan Street, Albany, California 94710, United States of America

Abstract—Traps baited with either ethyl (*E*,*Z*)-2,4-decadienoate (pear ester) or (*E*,*E*)-8,10-dodecadien-1-ol (codlemone) (Pherocon® CM-DA™ and Megalure CM™ lures, respectively) were used to develop action thresholds for codling moth (*Cydia pomonella* (L.)) in apple (*Malus domestica* Borkh.; Rosaceae) orchards treated with sex pheromones for control of this pest. Studies were conducted in 102 orchards treated with 500–1000 ISOMATE®-C PLUS dispensers per hectare during 2000–2002. Pairs of traps were placed within two 1.0-ha plots within each orchard. Fruit injury was assessed at mid-season and prior to harvest in each plot. The numbers of female and total moths caught in pear ester-baited traps and male moths caught in codlemone-baited traps were used to develop action thresholds. Thresholds were based on the minimum cumulative number of moths per trap in ≥95% of traps in unsprayed plots with no fruit injury. Specific thresholds were established for the first insecticide spray targeting the start of egg hatch and for the first and second moth flights. The proportion of plots with mid-season fruit injury that had cumulative moth catches below the action threshold at first spray and at second moth flight was determined using the established action threshold and thresholds reduced incrementally to ≥1 moth per trap. Moth catches below the threshold at first spray were less common in plots with high levels of fruit injury (>0.3%) than in plots with low levels of fruit injury and more common with codlemone-baited traps than with pear ester-baited traps. An action threshold of ≥1 moth in a pear ester-baited trap at first spray eliminated the error in predicting fruit injury in plots at mid-season. Conversely, a high proportion of traps baited with either lure failed to predict low levels of fruit injury at harvest in unsprayed plots regardless of the cumulative moth threshold used during the second moth flight.

Résumé—Des pièges appâtés à l'éthyl (*E,Z*)-2,4-décadiénoate (ester de poire; Pherocon^MD CM-DA^MC) ou au (*E,E*)-8,10-dodécadiènol (codlemone; Megalure CM^MC) ont servi à déterminer des seuils d'action pour la carpocapse de la pomme, *Cydia pomonella* (L.), dans des pommeraies à *Malus domestica* Borkh. (Rosaceae) traitées aux phéromones sexuelles pour la lutte contre ce ravageur. Les études ont été menées dans 102 vergers traités avec 500–1000 distributeurs ISOMATE^MD-C PLUS par hectare en 2000–2002. Nous avons placé des paires de pièges dans deux parcelles de 1,0 ha dans chaque verger. Nous avons évalué le dommage aux fruits à la mi-saison et juste avant la récolte dans chaque parcelle. Les nombres de papillons femelles et de papillons totaux dans les pièges appâtés d'ester de poire et de papillons mâles dans les pièges appâtés de codlemone ont servi à déterminer les seuils d'action. Nous avons choisi les seuils d'après le nombre cumulatif minimum de papillons récoltés par piège dans > 95 % des pièges dans les parcelles non traitées sans dommage aux fruits. Nous avons développé des seuils pour le premier arrosage d'insecticide qui cible le début de l'éclosion des oeufs et pour le premier et le second envol des papillons. Dans les parcelles présentant des dommages aux fruits en mi-saison, nous avons déterminé la proportion de pièges ayant des récoltes cumulatives sous le seuil d'action lors du premier arrosage et lors du second envol à l'aide du seuil d'action établi et à l'aide de seuils réduits de façon graduelle à ≥ 1 papillon par piège. Les récoltes de papillons sous le seuil lors du

Received 2 May 2005. Accepted 12 October 2005.

[1]Corresponding author (e-mail: aknight@yarl.ars.usda.gov).

premier arrosage sont moins communes dans les parcelles présentant un fort pourcentage (> 0,3 %) de dommages au fruits que dans celles qui en présentent peu et plus communes dans les pièges à la codelemone que dans les pièges à l'ester de poire. Un seuil d'action de ≥ 1 papillon dans un piège à l'ester de poire lors du premier arrosage élimine l'erreur dans la prédiction de dommages aux fruits en mi-saison. Inversement, une forte proportion des pièges munis de l'un ou l'autre appât ne réussissent pas à prédire les faibles intensités de dommages aux fruits au moment de la récolte dans les parcelles non traitées, quel que soit le seuil du nombre cumulé de papillons utilisé durant le second envol des papillons.

[Traduit par la Rédaction]

Introduction

An important prerequisite for successful management of codling moth, *Cydia pomonella* (L.) (Lepidoptera: Tortricidae), in apple, *Malus domestica* Borkh. (Rosaceae), has been the implementation of an intensive monitoring program (Vickers and Rothschild 1991). Male moth catch in codlemone-baited traps has been used to infer population density (Riedl and Croft 1974) and timing of first egg hatch (Riedl *et al.* 1976). Standardization of trap use has been suggested (Riedl 1980), but significant differences in trap and lure usage still exist (Riedl *et al.* 1986). The lack of standardized monitoring practices impacts moth catch (Knight and Christianson 1999), and action thresholds based on male moth catches in codlemone-baited traps vary widely among geographical areas (Vickers and Rothschild 1991).

Careful monitoring of codling moth in orchards treated with sex pheromone mating disruption is critical because of the influence of moth density on the success of mating disruption and the potential for undetected moth immigration into treated orchards (Cardé and Minks 1995). Typically, high-dose codlemone ((*E*,*E*)-8,10-dodecadien-1-ol) lures in traps placed in the top third of the tree canopy have been used to monitor codling moth in orchards treated with sex pheromone (Knight 1995). In addition, a higher density of traps has been recommended for treated *versus* conventional orchards (Gut and Brunner 1996). Action thresholds for codling moth in sex-pheromone-treated orchards based on cumulative counts of male moths captured during the first and second generations have been proposed (Gut and Brunner 1996).

The cumulative catch of male moths in codlemone-baited traps has been widely used as an estimator of gravid female density and oviposition timing because few options have been available to directly and easily monitor female codling moths (Knight and Croft 1991). However, a pear-derived kairomone for codling moth, (*E*,*Z*)-2,4-decadieonoate (pear ester), has been found to attract both sexes of codling moth (Light *et al.* 2001). A gray halobutyl septa loaded with 3.0 mg of pear ester and placed in a standard sticky trap has, in some cases, been more attractive for codling moth in sex-pheromone-treated orchards than high-dose codlemone lures (Thwaite *et al.* 2004; Knight *et al.* 2005). A number of factors have been found to influence the performance of pear ester in monitoring codling moth in pome fruits, including crop, cultivar, application of sex pheromone dispensers, lure loading, trap size, occurrence of fruit injury, and trap placement within the canopy (Knight and Light 2005). Efforts to standardize the use of pear ester to effectively monitor codling moth would likely accelerate the adoption of this attractant.

Here, we report the results of monitoring codling moth with pairs of traps baited with pear ester or codlemone lures in 204 plots within 102 apple orchards treated with sex pheromone dispensers during a 3-year period. Our objective was to compare the effectiveness of codlemone and pear ester-baited traps in predicting the occurrence of fruit injury at several time periods during the season. Action thresholds were developed for the first insecticide spray and for first and second moth flight with data collected from orchard plots not treated with insecticides and not having fruit injury. The probability of cumulative moth catch being less than the action threshold despite the occurrence of fruit injury was evaluated for both female and total numbers of moths caught in pear ester-baited traps and for male moths caught in codlemone-baited traps early and late in the season. Factors likely affecting the implementation of pear ester-baited traps to monitor codling moth in sex-pheromone-treated apple orchards are discussed.

Materials and methods

Study sites

Studies were conducted in 22, 50, and 30 apple orchards during 2000, 2001, and 2002, respectively. All orchards were situated within a 64-km^2 area near Brewster, Washington (48°N, 119°W). Orchards were 8–16 ha and were planted at 500–1000 trees/ha, and tree heights ranged from 3.0 to 5.1 m. Orchards were typically mixed, with the dominant cultivar making up >75% of the area. Orchards monitored in 2000 included 10 each of *M. domestica* 'Delicious' and 'Granny Smith' and 1 each of 'Golden Delicious' and 'Fuji'. Ten orchards each of 'Delicious', 'Gala', 'Golden Delicious', 'Fuji', and 'Granny Smith' were monitored in 2001. Study sites in 2002 comprised 10 orchards each of 'Gala', 'Fuji', and 'Granny Smith'. All orchards were treated with 500–1000 ISOMATE®-C PLUS dispensers (Pacific Biocontrol, Vancouver, Washington) per hectare. Dispensers were loaded with 182.3 mg of a 60:33:7 blend of codlemone, dodecanol, and tetradecanol.

Records of the use of organophosphate insecticides (azinphosmethyl (Micro Flo Company, Memphis, Tennessee) and phosmet (Zeneca Ag Products, Wilmington, Delaware)) and the insect growth regulator methoxyfenozide (Dow AgroSciences, Indianapolis, Indiana) were collected for all orchards monitored during the study. Insecticides were applied either to the entire orchard or only along borders. The mean ± SE number of sprays applied was 2.7 ± 0.4, 1.3 ± 0.3, and 2.8 ± 0.4 in 2000, 2001, and 2002, respectively. The mean ± SE number of sprays applied to borders was 0.7 ± 0.2, 0.4 ± 0.1, and 0.0 in the same 3 years, respectively. The sprays were apportioned nearly equally between the first and second moth generations.

Two plots separated by 150 m were established within each orchard. Two delta-shaped traps with removable sticky liners were placed in each plot, 50 m apart and 25 m from the physical edge of the orchard. One trap was baited with a high-load codlemone lure (Pherocon® Megalure CM™, Trécé Inc., Adair, Oklahoma) and the other with a pear ester lure (Pherocon® CM-DA™, Trécé Inc.). Traps were attached to 1.5-m plastic poles and hung in the upper third of the canopy. Traps were placed in orchards on 26 April 2000, 3 May 2001, and 1 May 2002 and monitored for 18 weeks until September. All traps were checked weekly except during week 9 in 2001 and the first week in 2002. Moths were removed from traps and sexed. The sticky trap liners were replaced every few weeks and lures were replaced once during each season after 9 weeks.

Fruit injury from codling moth was assessed in all plots at mid-season (early July) and prior to harvest of each cultivar (early to mid-September). Fifteen low and 15 high fruit from 40 trees (1200 fruit per plot) were visually inspected for injury on each date. Sampled trees were selected along transects within 25 m of either trap within the plot (a 50 m × 100 m area).

Fifty-four plots (27 orchards) were left unsprayed over an entire season during the 3-year study. The majority of these plots (78%) were in 2001 because of the inclusion of a larger number of plots and the reduced application of insecticides in this year compared with the other 2 years. These data were fairly evenly divided among four of the five cultivars (each constituting 22%–30% of the total), but no plots of 'Granny Smith' were included. Similarly, the same four cultivars were included among the 11 unsprayed plots that had measurable levels of fruit injury at harvest.

Seventy-six plots were not sprayed with insecticides until mid-season. Again, the majority of these plots were in 2001 (55%), and the same four cultivars were fairly evenly represented (18%–29%). However, four plots of 'Granny Smith' from 2000 were also included in this group. Plots with levels of fruit injury >0.3% at harvest included plots of 'Granny Smith' and 'Delicious'. All cultivars except 'Granny Smith' were included in the group of plots with low levels of fruit injury at harvest (≤ 0.3%).

Thirty-seven plots had fruit injury at mid-season and were sprayed with insecticides during the first moth flight. These included plots of 'Delicious', 'Fuji', and 'Granny Smith', with the latter making up 78% of the group. All the plots included in the highest class of fruit injury (>0.3%) were plots of 'Granny Smith'.

The timing of the first insecticide spray was defined as the accumulation of 139 degree-days above a lower developmental threshold of 10 °C following the start of sustained catch of male moths (Biofix) in a codlemone-baited trap and corresponds to 2.0% egg hatch (Beers and Brunner 1992). The date of Biofix for this region (Brewster, Washington) was determined by the Washington State University Extension

Service and was posted on their Web site (http://www.ncw.wsu.edu/treefruit). The Biofix dates were 27 April 2000, 7 May 2001, and 2 May 2002. Temperatures were monitored with a grid of three DataScribe loggers (Avatel, Fort Bragg, California) placed within the region. Because traps in our study were checked only once per week, the cumulative moth counts for first spray timing were actually accumulated over 124, 158, and 115 degree-days after Biofix in 2000, 2001, and 2002, respectively.

Action thresholds were developed only with data collected from plots in unsprayed orchards with no fruit injury and were established for three time points during the season: first spray, first moth flight, and second moth flight. Only data collected from the 52 plots unsprayed at mid-season and with no fruit injury were used to develop action thresholds for both first spray timing and first moth flight. Moth catch data from the 43 plots with no injury at harvest and unsprayed all season were used to develop action thresholds for the second flight period. Action thresholds were established for female and total moths caught in pear ester-baited traps and male moths caught in codlemone-baited traps.

The criterion we used to establish each action threshold was the minimum cumulative number of moths per trap at each time point in ≥95% of traps in unsprayed plots without fruit injury. We selected the 95th percentile ($1 - \beta$) to set the threshold high enough to avoid unnecessary sprays while ignoring a few outliers (type II error) (Dixon and Massey 1969). This approach was used instead of regression of fruit injury *versus* moth catch for several reasons. First, regressions for the first spray timing and first moth flight would be meaningless because all plots with injury at mid-season were sprayed with insecticides. Instead, we used a categorical approach that considered the presence or absence of injury. Injury was further classified into two levels, ≤0.3% and >0.3%. The data tended to break into these two classes, with plots in the higher injury class having 0.5%–2.1% injury; the lower injury class was equivalent to sampling only 1–3 injured fruit per 1200 fruit in each plot. A regression approach could have been used for the second moth flight, as 11 unsprayed plots had detectable injury at harvest. However, we decided that since injury in these plots ranged from 1 to 3 fruits per sample and moth catches ranged from 0 to 6 per trap, this approach would be trivial.

The proportion of traps with cumulative moth catches that failed to reach the established action threshold was evaluated for the first spray timing using 37 plots with fruit injury at mid-season and for second moth flight using 11 plots with injury at harvest. Unfortunately, moth catches during the first moth flight could not be assessed because of the application of insecticides during this time period in all orchards with mid-season fruit injury. The proportion of traps in plots with fruit injury failing to reach the action threshold was evaluated for thresholds from ≥1 moth per trap to the established action threshold. The proportion for the first spray timing was segregated between plots with ≤0.3% (n = 25) and >0.3% fruit injury (n = 12).

Mean cumulative moth catch per trap was summarized for plots unsprayed until the first insecticide application (n = 204) and the first (n = 76) and second moth flights (n = 54) based on levels of fruit injury at mid-season and harvest. All count data were square root ($(x + 0.01)^{0.5}$) transformed before conducting analysis of variance (ANOVA) (Analytical Software 2003). Where significant differences ($P < 0.05$) in ANOVA occurred, means were separated with a least significant difference test.

Results

Significant differences in the cumulative moth counts of total and female moths in pear ester-baited traps and male moths in codlemone-baited traps at different points during the season were found among plots grouped as having no injury or injury levels of ≤0.3% or >0.3% (Table 1). Most notably, cumulative moth counts at first spray were significantly different for all three measures of moth catch among plots with no injury and plots with mid-season injury levels of ≤0.3% and >0.3% (Table 1). Counts were highest in plots with the highest level of injury and lowest in plots with no injury. A different pattern occurred in cumulative moth counts during first flight for plots grouped by injury at harvest (Table 1). For example, mean catch of moths in pear ester-baited traps was significantly higher in plots with high levels of fruit injury than in plots with low levels of injury or no injury. The mean catch of male moths in codlemone-baited traps was significantly lower in plots with no injury compared with plots with either low or high levels of injury. No difference was found in the mean catch of female moths among these three

Table 1. Mean ± SE cumulative catches of codling moth (*Cydia pomonella*) in traps baited with codlemone or pear ester at different time periods within apple (*Malus domestica*) plots with and without fruit injury.

		Mean ± SE (min.–max.) cumulative no. of moths per trap		
		Pear ester		Codlemone
Time period	Level of fruit injury (no. of plots)	Total moths	Female moths	Male moths
Up to first spray	0.0% (167)	0.2±0.04*c* (0–2)	0.04±0.01*c* (0–1)	0.8±0.2*c* (0–11)
	≤0.3% (25)	4.6±1.0*b* (1–6)	1.0±0.2*b* (0–3)	4.6±1.2*b* (0–23)
	>0.3% (12)	20.0±5.2*a* (8–57)	10.2±2.9*a* (3–31)	12.1±5.9*a* (0–75)
	ANOVA df = 2, 201	$F = 109.1$, $P < 0.0001$	$F = 105.2$, $P < 0.0001$	$F = 27.2$, $P < 0.0001$
First flight	0.0% (52)	0.6±0.1*b* (0–4)	0.1±0.1 (0–1)	0.7±0.2*b* (0–5)
	≤0.3% (14)	0.6±0.3*b* (0–3)	0.2±0.1 (0–1)	2.6±1.1*a* (0–13)
	>0.3% (10)	2.0±0.4*a* (1–5)	0.5±0.3 (0–3)	5.6±2.7*a* (0–27)
	ANOVA df = 2, 73	$F = 8.83$, $P < 0.001$	$F = 1.57$, $P = 0.22$	$F = 7.85$, $P < 0.001$
Second flight	0.0% (43)	0.8±0.32 (0–10)	0.3±0.12 (0–4)	0.4±0.2 (0–4)
	≤0.3% (11)	1.4±0.45 (0–6)	0.7±0.24 (0–3)	0.4±0.2 (0–2)
	ANOVA df = 1, 52	$F = 2.43$, $P = 0.13$	$F = 2.53$, $P = 0.12$	$F = 0.28$, $P = 0.60$

Note: No insecticide sprays were applied in plots up to the selected time period. First spray is timed to occur after the accumulation of approximately 139 degree-days from the beginning of moth flight. Levels of fruit injury were assessed at mid-season for first spray timing and prior to harvest for first and second moth flight. For each time period, means within a column followed by different letters are significantly different (LSD test, $P < 0.05$). ANOVA was not conducted for cumulative moth counts during first flight in plots with variable levels of mid-season fruit injury since all plots with injury were sprayed prior to fruit sampling. Mean ± SE cumulative moth counts (range in parentheses) for the 76 unsprayed plots with no injury at mid-season were as follows: pear ester, total moths, 0.8 ± 0.1 (0–5); pear ester, female moths, 0.2 ± 0.1 (0–3); and codlemone, male moths, 1.7 ± 0.4 (0–27).

groups of plots (Table 1). No differences in moth catches were found during the second moth flight between plots with and without fruit injury.

Action thresholds developed for total and female moths in pear ester-baited traps and male moths in codlemone-baited traps varied and were not consistent throughout the season (Table 2). The lowest threshold was ≥1 female moth in a pear ester-baited trap at first spray and the highest was ≥4 male moths in a codlemone-baited trap at all three time points (Table 2). Action thresholds increased by 1 moth for both total moths and female moths in pear ester-baited traps from the first spray to first moth flight and remained unchanged for second moth flight (Table 2).

The proportion of plots with mid-season fruit injury with cumulative moth catches less than action thresholds at first spray (classification error) varied widely among the three types of thresholds: male moths with codlemone > female moths with pear ester > total moths with pear ester (Table 3). The occurrence of this type of error with codlemone-baited traps was reduced in plots with higher *versus* lower levels of fruit injury. No classification errors occurred in plots with high levels of fruit injury with either pear ester-based threshold. Reducing the action thresholds for total moths caught in pear ester-baited traps to ≥1 moth eliminated any error in predicting fruit injury in all plots regardless of the level of fruit injury. Incremental reductions in the action threshold for males caught in codlemone-baited traps also reduced this error but did not eliminate it completely (Table 3).

Prediction of low levels of fruit injury in 11 plots unsprayed all season based on cumulative moth catch thresholds was poor (Table 3). Reducing the action thresholds for male moths caught in a codlemone-baited trap and total or female moths caught in a pear ester-baited trap during the second moth flight to ≥1 moth only marginally reduced the proportion of classification errors (Table 3).

Discussion

Action thresholds based on the capture of male codling moths in codlemone-baited traps have been used for 30 years in orchards not treated with sex pheromone and have allowed growers to effectively reduce their use of insecticides (Vickers and Rothschild 1991). In general, action thresholds have varied across the major fruit-growing regions of the world from 2 to 5 moths per trap caught for 1 to 2 consecutive weeks (Riedl *et al.* 1986; Vickers and Rothschild 1991). Typically, these thresholds have been developed from a small set of both sprayed and unsprayed orchards — 6 apple orchards (Vakenti and Madsen 1976), 21 apple orchards (Riedl and Croft 1974), 5 walnut orchards (McNally and Van Steenwyk 1986), and 4 pear orchards (Westigard and Graves 1976) — and a standardized protocol for monitoring codling moth has not been used.

A large number of factors can influence moth catch in codlemone-baited traps, including trap and lure type, trap and lure maintenance, trap density, trap placement in the tree canopy, and trap location within the orchard (Riedl *et al.* 1986). Knight and Christianson (1999) calculated that different combinations of these factors could contribute to a 192-fold difference in catch of codling moth over a 3-week period. Other factors such as crop, cultivar, the application of insecticide sprays, immigration of moths from outside sources, yearly climatic variation, and the accepted economic injury level for codling moth also influence the establishment of action thresholds for codling moth (Vickers and Rothschild 1991).

These same factors impact the development of action thresholds for codling moth in sex-pheromone-treated apple orchards. Gut and Brunner (1996) suggested action thresholds for codling moth based on their experience with a large but unspecified number of apple orchards in Washington State. Their thresholds were based on a standardized monitoring program that utilized a red rubber septum loaded with 10.0 mg of codlemone in a wing-style trap placed at mid-canopy height at a density of one trap per hectare. They concluded that orchards with cumulative moth catches of <4 per trap during first flight did not need any supplemental insecticide sprays (Gut and Brunner 1996).

Significant differences exist between our monitoring protocol with codlemone-baited traps and that recommended by Gut and Brunner (1996), including differences in sex pheromone lure, trap type, and trap placement within the canopy. The Megalure CM™ is significantly more attractive than the 10.0-mg red rubber septa for codling moth and does not need to be changed as frequently (8–10 *versus* 2–3 weeks) (Knight 2002). Delta traps caught significantly more codling moths than wing

Table 2. Action thresholds based on cumulative numbers of codling moths (*Cydia pomonella*) caught in delta traps baited with either codlemone or pear ester during selected time periods throughout the season.

	Action thresholds (no. of moths/trap)		
	Pear ester		Codlemone
Time period	Total moths	Female moths	Male moths
Up to first spray	≥2	≥1	≥4
First flight	≥3	≥2	≥4
Second flight	≥3	≥2	≥4

Table 3. Proportion of plots with fruit injury in which the cumulative catch of codling moths (*Cydia pomonella*) in traps baited with either codlemone or pear ester failed to reach the action thresholds at first spray (accumulation of 139 degree-days after Biofix) and during second moth flight.

	Proportion of plots misclassified using different action thresholds								
	Pear ester					Codlemone			
	No. of moths			No. of female moths		No. of male moths			
Level of fruit injury (no. of plots)	≥1	≥2	≥3	≥1	≥2	≥1	≥2	≥3	≥4
				First spray					
≤0.3% (25)	0.00	0.20	—	0.32	—	0.20	0.40	0.52	0.68
>0.3% (12)	0.00	0.00	—	0.00	—	0.08	0.08	0.33	0.42
				Second moth flight					
≤0.3% (11)	0.36	0.45	0.73	0.55	0.64	0.55	0.73	0.82	1.00

Note: Fruit injury was sampled in all plots included in this assessment of action thresholds at mid-season and before harvest for first spray timing and second moth flight, respectively.

traps did in both laboratory and field tests (Knight *et al.* 2002). Traps placed high in the canopy catch significantly more codling moths than traps placed at mid-canopy (Knight 1995). Yet, despite these differences, our action thresholds developed for codlemone-baited traps at first spray and first moth flight were identical to those of Gut and Brunner (1996).

Seasonally based action thresholds for codling moth were established from unsprayed orchard plots with no fruit injury to avoid unnecessary insecticide sprays. Action thresholds need to be high enough to allow the incidental catch of moths to be ignored. The rate of male codling moths immigrating into sex-pheromone-treated orchards can be much higher than the rate for female moths because of the male's attraction to both the codlemone lures in traps and the sex pheromone dispensers (Witzgall *et al.* 1999). Codlemone-baited traps placed on the borders of orchards can have much higher male moth catches than similar traps placed in the interior of orchards (Vakenti and Madsen 1976; Westigard and Graves 1976; Knight 1995). The recapture rate of marked codling moth adults released at several distances from traps suggests that the drawing range of pear ester lures for both sexes is much shorter than that of codlemone lures for male moths (Knight and Light 2005). Yet the influence of trap location within an orchard on moth catches in pear ester-baited traps or its relation with nearby levels of fruit injury has not been examined. In addition, there is likely no acceptable level of cumulative female codling moth catch in orchards with fruit headed for export markets, though action thresholds of ≥2 female moths per trap were established for both the first and second flight periods.

Growers probably rely on monitoring traps more to be warned of crop-injuring pest population densities than to avoid unnecessary sprays. The frequent failure of codlemone-baited traps to predict fruit injury is a serious concern, especially in sex-pheromone-treated orchards. During our 3-year test, the pear ester-baited trap was more effective than the codlemone-baited trap in predicting the occurrence of fruit injury within unsprayed plots. For example, in no case did the use of an action threshold based on the pear ester lure fail to predict fruit injury in plots with relatively high levels of fruit injury at mid-season. In fact, the threshold of ≥1 moth in a pear ester-baited trap generated no classification errors in any plot with mid-season fruit injury. Conversely, classification errors were more common with a female-only threshold of ≥1 female moth per trap in plots with low levels of fruit injury at mid-season. The occurrence of these errors with traps baited with codlemone was reduced by lowering the action threshold, but the errors were not eliminated even at a threshold of ≥1 moth per trap in plots with high levels of fruit injury.

Prediction of low levels of fruit injury (<0.3%), particularly later in the season, was more difficult than prediction of high levels of injury with the use of either codlemone- or pear ester-baited traps. The resolution in monitoring low population densities of codling moth in orchards with traps is limited (Riedl and Croft 1974; Knight *et al.* 1995). Growers can further reduce their risk of not detecting infestations by increasing the density of traps, focusing more intensive monitoring efforts in known problem areas of orchards, and implementing an effective season-long pest management program (Gut and Brunner 1996). Conversely, acceptance of fruit injury levels in the range of 0.3% at harvest may be reasonable in many orchards since post-harvest sorting practices can further sanitize fruit shipments prior to export (Hansen and Schievelbein 2002).

A standardized monitoring program for codling moth using pear ester has been developed to minimize the influence of various factors on moth catch (Knight and Light 2005). The protocol includes the use of a gray halobutyl septum loaded with 3.0 mg of pear ester and placed in a delta-shaped trap hung in the upper third of the orchard's canopy. Traps are used at a density of 1 per hectare and are placed 25 m from the edge of the orchard. However, other factors that may also influence the performance of the pear ester-baited traps, such as cultivar and level of fruit injury, cannot be standardized across orchards. Pear ester-baited traps are more attractive relative to codlemone-baited traps in plots of 'Granny Smith' than in plots of many other cultivars (Knight and Light 2005). Unfortunately, nearly all of the 'Granny Smith' orchards in our study were sprayed with insecticides and could not be included in the development of action thresholds. Further studies are needed to develop action thresholds for codling moth with pear ester-baited traps in this important cultivar. The occurrence of fruit injury in 'Bartlett' pear orchards significantly reduced catches of codling moth in pear ester-baited traps (Knight *et al.* 2005). A similar effect in apple orchards has not been reported; however, moth catch in pear ester-baited traps adjacent to injured 'Fuji' fruits was not reduced compared with moth catch in traps placed 1.0 m from fruit (Knight and Light 2005). Determining the utility of action thresholds based on codling moth catches in pear ester-baited traps will require several years of field testing under a broad range of conditions. A synthesis of these results may help to identify aspects of this protocol that need to be adjusted and speed the adoption of pear ester as an effective monitoring tool for codling moth.

Acknowledgements

We thank T. and M. Goehry (Brewster, Washington) for their help in setting up the field studies and collecting data. We also thank B. Lingren (Trécé Inc., Adair, Oklahoma) for providing the traps and lures used in these studies. The paper was strengthened by the helpful comments made by H. Riedl, Mid-Columbia Experiment Station, Oregon State University, Hood River, Oregon; P. Landolt, USDA Agricultural Research Service, Wapato, Washington; C. Vincent, Agriculture Canada, Quebec, Canada; and T. Lesky, USDA Agricultural Research Service, Kearneysville, West Virginia. This research was partially funded by the Washington Tree Fruit Research Commission, Wenatchee, Washington.

References

Analytical Software. 2003. Statistix8 [computer program]. Analytical Software, Tallahassee, Florida.

Beers, E.H., and Brunner, J.F. 1992. Implementation of the codling moth phenology model on apples in Washington State, USA. Acta Phytopathologica et Entomologica Hungarica, **27**: 97–102.

Cardé, R.T., and Minks, A.K. 1995. Control of moth pests by mating disruption: successes and constraints. Annual Review of Entomology, **40**: 559–585.

Dixon, W.J., and Massey, F.J. 1969. Introduction to statistical analysis. McGraw-Hill Book Company, New York.

Gut, L.J., and Brunner, J.F. 1996. Implementing codling moth mating disruption in Washington pome fruit orchards. Tree Fruit Research Extension Center Information Series, No. 1. Washington State University, Wenatchee, Washington.

Hansen, J.D., and Schievelbein, S. 2002. Apple sampling in packing houses supports the systems approach for quarantine control of codling moth. Southwestern Entomologist, **27**: 277–282.

Knight, A. 1995. The impact of codling moth (Lepidoptera: Tortricidae) mating disruption on apple pest management in Yakima Valley, Washington. Journal of the Entomological Society of British Columbia, **92**: 29–38.

Knight, A.L. 2002. A comparison of gray halo-butyl elastomer and red rubber septa to monitor codling moth (Lepidoptera: Tortricidae) in sex pheromone-treated orchards. Journal of the Entomological Society of British Columbia, **99**: 123–132.

Knight, A., and Christianson, B. 1999. Using traps and lures in pheromone-treated orchards. Good Fruit Grower, **50**: 45–51.

Knight, A.L., and Croft, B.A. 1991. Modeling and prediction technology. *In* Tortricoid pests. *Edited by* L.P.S. van der Geest and H.H. Evenhuis. Elsevier, Amsterdam. pp. 301–312.

Knight, A.L., and Light, D.M. 2005. Factors affecting the differential capture of male and female codling moth (Lepidoptera: Tortricidae) in traps baited with ethyl (*E*, *Z*)-2,4-decadienoate. Environmental Entomology, **34**: 1161–1169.

Knight, A.L., Larson, D., and Christianson, B. 2002. Flight tunnel and field evaluations of sticky traps for monitoring codling moth (Lepidoptera: Tortricidae) in sex pheromone-treated orchards. Journal of the Entomological Society of British Columbia, **99**: 107–116.

Knight, A.L., VanBuskirk, P., Hilton, R., Zoller, B., and Light, D.M. 2005. Monitoring codling moth (Lepidoptera: Tortricidae) in four cultivars of pear. Acta Horticulturae, **671**: 565–569.

Light, D.M., Knight, A.L., Henrick, C.A., Rajapaska, D., Lingren, B., Dickens, J.C., Reynolds, K.M., Buttery, R.G., Merrill, G., Roitman, J., and Campbell, B.C. 2001. A pear-derived kairomone with pheromonal potency that attracts male and female codling moth, *Cydia pomonella* (L.). Naturwissenschaften, **88**: 333–338.

McNally, P.S., and Van Steenwyk, R. 1986. Relationship between pheromone trap catches and sunset temperatures during the spring flight to codling moth (Lepidoptera: Olethreutidae) infestations in walnuts. Journal of Economic Entomology, **79**: 444–446.

Riedl, H. 1980. The importance of pheromone trap density and trap maintenance for the development of standardized monitoring procedures for the codling moth (Lepidoptera: Tortricidae). The Canadian Entomologist, **112**: 529–544.

Riedl, H., and Croft, B.A. 1974. A study of pheromone trap catches in relation to codling moth damage. The Canadian Entomologist, **106**: 525–537.

Riedl, H., Croft, B.A., and Howitt, A.J. 1976. Forecasting codling moth phenology based on pheromone trap catches and physiological time models. The Canadian Entomologist, **108**: 449–460.

Riedl, H., Howell, J.F., McNally, P.J., and Westigard, P.H. 1986. Codling moth management: use and standardization of pheromone trapping systems. Bulletin 1918, University of California Division of Agriculture and Natural Resources, Oakland, California.

Thwaite, W.G., Mooney, A.M., Eslick, M.A., and Nichol, H.L. 2004. Evaluating pear-derived kairomone lures for monitoring *Cydia pomonella* (L.) (Lepidoptera: Tortricidae) in Granny Smith apples under mating disruption. General and Applied Entomology, **33**: 56–60.

Vakenti, J.M., and Madsen, H.F. 1976. Codling moth (Lepidoptera: Tortricidae): monitoring populations in apple orchards with sex pheromone traps. The Canadian Entomologist, **108**: 433–438.

Vickers, R.A., and Rothschild, G.H.L. 1991. Use of sex pheromones for control of codling moth. *In* Tortricoid pests. *Edited by* L.P.S. van der Geest and H.H. Evenhuis. Elsevier, Amsterdam. pp. 339–354.

Westigard, P.H., and Graves, K.L. 1976. Evaluation of pheromone baited traps in a pest management program on pears for codling moth control. The Canadian Entomologist, **108**: 379–382.

Witzgall, P., Bäckman, A.-C., Svensson, M., Koch, U.T., Rama, F., El-Sayed, A., Brauchi, J., Arn, H., Bengtsson, M., and Löfqvist, J. 1999. Behavioral observations of codling moth, *Cydia pomonella*, in orchards permeated with synthetic pheromone. Biocontrol, **44**: 211–237.